Phase curves of selected particulate materials: The reflectance related contribution of coherent backscattering to the opposition surge.

by

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Proposed Running Head: Coherent Backscattering Opposition Effect

Abstract

We present angular scattering measurements of a suite of particulate materials of mixed particle size. Our results provide strong support for the hypothesis that coherent back-scattering rather than shadow hiding is the principal contributor to the enhanced reflectance seen in planetary regolith materials when observed at small phase angles, commonly known in the planetary science community as the opposition effect. The reflectance of the samples varied from 3-99%.

Eight samples were each presented with both senses of linearly and circularly polarized light and the phase curves were measured. The circular polarization ratio was observed to increase in all the samples as the phase angle of the observation decreased. This result is consistent with the predictions made by the coherent backscattering hypothesis. The shadow hiding model predicts that the circular polarization ratio should decrease as the phase angle of the observation decreases.

The more reflective materials exhibit stronger opposition surges than the less reflective ones. We find a non-linear relationship between the slope of the opposition curve measured at 2° and the single scattering albedo of the sample. This is the opposite of what is predicted by the shadow hiding model for the opposition effect. These results provide strong support for case that coherent backscattering is the major contributor to the opposition effect.

Introduction

For more than a hundred years it has been known that solar system objects which present particulate surfaces to the observer exhibit a non-linear increase in intensity of reflected electromagnetic radiation when observed at progressively smaller phase angles (see Hapke, 1993, p2 16-235). This effect is also seen in goniometer measurements on particulate samples in the laboratory (e.g. Hapke and van Horn, 1963; Oetking, 1966; Pleskot, 1981), In the planetary science community this phenomenon is known as the opposition surge (e.g. Veverka, 1977a). The traditional interpretation of this effect is that mutual shadowing between the regolith particles is reduced as the observer moves closer to zero phase angle. As the shadowing decreases, the intensity of the reflected light increases (Hapke, 1963; Irvine, 1966; Hapke, 1986).

The reflection of electromagnetic radiation from a planetary regolith involves a combination of geometric and physical optics processes which contribute to the signal returned to the remote observer. The geometric optics effects are the product of singly and multiply scattered radiation from the surfaces of the regolith particles, combined with radiation which has undergone various combinations of transmission through one or more regolith grains followed by one or more scattering from other particles. The physical optics effects include diffraction of radiation around the edges of large irregular particles and cooperative coherent scattering between particles which are small when compared to the wavelength of the incident radiation. These effects produce measurable changes in the reflectance and polarization of reflected light as a function of illumination and viewing geometry.

The shadow hiding interpretation of the opposition effect is entirely a geometrical optics phenomenon. Therefore, it is applicable only in situations where the particles which cast shadows on the regolith are larger than the wavelength of the light at which the observation is made. The shadow hiding interpretation of the opposition effect assumes that the brightness surge occurs because near 0° phase each particle hides its own shadow. The angular width of the shadow hiding opposition effect peak is of the order of the ratio of the sizes of the grains to the extinction length in the medium. The ratio of the height of the peak at 0° phase angle to the continuum intensity theoretically can be as large as two (Hapke, 1990).

For objects with high albedo such as the icy satellites of the giant outer planets, the shadow hiding hypothesis predicts that the opposition surge will be reduced or non-existent because the multiple scattering of light between regolith particles would fill in the shadows. This expectation remained a conjecture until recently because earthbased observations of the bright icy, satellites of the outer solar system could not be done at phase angles large enough to determine the shape of the phase curve. A few phase angle measurements at near 0° are not sufficient to determine the size of the surge. It was only with the observations from the Voy -

ager spacecraft of the satellites of the outer solar system that the phase curves of the high albedo, icy satellites were determined over a wide range of phase angles. The Voyager observations of the satellites of Uranus and Neptune (some of which are highly reflective) when combined with groundbased observations near zero degrees phase established that these objects have strong, narrow opposition peaks (Brown and Cruikshank, 1983; Nelson *et al.*, 1987). This very low phase, very pronounced, opposition effect has also been reported in Voyager and ground based observations of Europa as well (Domingue, *et al.*, 1989). A repeated analysis of the Uranian satellite data set of Nelson *et al., (1987)* which combined PPS observations with the imaging system observations has confirmed the earlier PPS result (Buratti *et al.*, 1990).

In this paper we present evidence from laboratory studies that the opposition effect seen in the bright icy satellites of the outer solar system is not caused by shadow hiding but by an entirely different phenomenon, coherent backscatteri ng. The coherent backscatter effect is a constructive interference phenomenon which occurs at small phase angles in particulate media in which the scatterers are the size of the wavelength of the incident light. It is predicated on the assumption that portions of the same wave front traveling in opposite directions along the same multiple scattering path within a particulate medium will exhibit constructive interference effects after exiting from the medium. This will happen when the difference in path length is of the size of the wavelength of the incident radiation. At very small phase angles these rays combine coherently to produce a sharp intensity peak. The angular width of the peak (FWHM) is $\frac{\lambda}{2\pi D}$ where D is the photon mean free path in the medium. It is predicted that in order for the coherent backscattering phenomenon to occur, the scatterers' size must be at least of the order of the wavelength of the incident light.

The coherent backscattering phenomenon has been discussed in the solid state physics community where it is also known as coherent constuctive interference, weak localization, or time reversal symmetry (Akkermans et al., 1986; Mackintosh and John, 1988). Coherent backscattering has been suggested as the process which explains the unusual reversal in circular polarization that is observed in the radar backscatter measurements of the Galilean satellites (Hapke, 1990; Hapke and Blewett, 1991; Ostro *et al.*, 1991). Recent theoretical treatments of the problem have developed a vector formulation of the coherent backscattering reflection process which is necessary to deal correctly with the radar polarization measurements. The coherent backscattering process explains the radar measurements of the outer satellites of the solar system (Peters, 1992).

The coherent backscattering mechanism predicts a testable dependence of the opposition surge on wavelength and albedo of the scattering mate.rial. Also, if linearly or circularly polarized light is incident, the coherent backscattering model predicts specific behavior in the polarization of the reflected light as a function of phase angle. The important testable predictions from this theory, which distinguish shadow hiding opposition effects from coherent backscattering opposition effects are:

1) Brightness effects. Shadow hiding is important for singly scattered light. Coherent backscattering, however, requires at least 2 scattering. For highly reflective materials, where multiple scattering is important, coherent backscattering is expected to predominate. At 0°, backscattered radiation coherently combines so that for high albedo objects the reflected component can be almost twice that expected based on shadow hiding alone. This intensity rapidly falls off at phase angles greater than a few tenths of a degree.

2) Wavelength effects. The angular width of the peak of a phase curve from a surface in which shadow hiding is the dominant process depends on the mean separation between scatterers and the size distribution of the particles. 1 t is independent of the wavelength of the incident radiation. However, coherent backscattering, an interference phenomenon, will result in the angular width of the peak of the phase curve being wavelength-dependent.

3) Linear polarization effects. Single reflections of incident linearly polarized light preserve the linear polarization direction in the reflected radiation. Multiple scattering tends to randomize the polarization of the reflected light. A phase curve of a surface in which shadow hiding is the dominant contributor to the opposition effect would be expected to be polarized in the same direction as the incident radiation. For a multiple scattering surface (where coherent backscattering is the dominant mechanism) the reflected phase curve would be much less polarized. In the case of perfect Raleigh scatterers, the ratio of the light polarized in the unexpected sense to the expected sense is predicted to be 50% (Stephen and Cwilich, 1986).

4) Circular polarization effects. If the incident radiation is circularly polarized, then the reflected singly scattered light is in the opposite helicity of the incident polarization. Multiple scattering from anisotropic scatterers will tend to preserve the circular polarization sense of the radiation returned to the observer because coherent backscattering involves successive multiple transmissions each of which preserves the incident helicity. Therefore, the shadow hiding opposition effect peak will have a circular polarization that is dominated by light of the opposite sense from that of the polarization of the incident light. The circular polarization ratio, μ_c is defined as the ratio of the intensity of light scattered with the same helicity as the incident light to the intensity scattered with the opposite helicity. ordinarily, in a shadow hiding opposition effect peak, μ_c is < 1, and decreases as the phase angle is decreased. However, theory predicts that in a coherent backscattering opposition effect peak μ_c increases and may become > 1 (Hapke, 1990; Mackintosh and John, 1988). A coherent backscattering opposition effect peak will be dominated by light with the same circular polarization as that of the incident light. Therefore, the size of the circular polarization ratio as a function of phase angle

is the measurement which distinguishes between coherent backscattering and shadow hiding. In this study we report the phase curves and circular polarization ratios of a suite of samples of differing albedo as a function of phase angle. The. slope of the phase curve near 0° and the size of the circular polarization ratio are plotted as a function of reflectance of the sample in order to distinguish between the shadow hiding and coherent backscattering processes and the contribution of each to the opposition effect.

Experiment Description

Our initial efforts in this investigation have been directed toward verification of our laboratory procedures used to distinguish unambiguously between the coherent backscattering and shadow hiding mechanisms. The principal disci iminator between the two mechanisms is the change in circular polarization ratio with phase angle of the observation. The shadow hiding hypothesis predicts that the circular polarization ratio will decrease with decreasing phase angle, the coherent backscattering hypothesis predicts that the circular polarization ratio will increase with decreasing phase angle. Therefore we measured the circular polarization ratio change with phase angle in addition to the phase curve of the sample.

The instrument used to make these measurements was the 1 m (short arm) goniometer of the planetary surfaces laboratory, Earth and Space Sciences Division, of the Jet Propulsion Laboratory. The instrument has been considerably modified and improved since its original description (Buratti *et al.*, 1988). The modifications permit us to present samples with two orthogonal senses of linearly polarized light and opposite senses of circularly polarized light. The detector can also measure both senses of linear and circular polarization in the reflected radiation. A drawing of the optical path followed by the light in the apparatus is shown in figure 1.

For this experiment an He-Ne laser course from Melles Gryot Co. was used with an output of 5 mw at 0.633pm. The horizontal laser source was positioned such that rotation about its long axis permitted the linear polarization of the output beam to be oriented at 45° to the scattering plane. The beam was chopped at 111 Hz and the detector amplifier was synchronized to reject signals not chopped at this rate. The output beam from the chopper was passed through a two position polarizer which' rendered the output beam either parallel or perpendicular to the scattering plane.

The linearly polarized beam next struck a first surface mirror which deflected the beam vertically downward to the sample. A quarter wave plate could be mechanically inserted into the vertical beam which permitted us to present the sample with either left or right handed circularly polarized light depending on the orientation of the linear polarizer which preceded it in the optical path. The sample cup was rotated at 0.5 Hz in order to average the effect of speckle in the scattered beam. The detector foreoptics included a four position filter wheel which permitted us to sample the reflected light in both directions of circular polarization and two directions of linear polarization, one in the scattering plane and one perpendicular to the scattering plane. The light passed through a 0.633pm notch filter prior to entering the detector.

Each sample was presented with linearly polarized light that was in the scattering plane and with linearly polarized light that was perpendicular to the scattering plane. In each case, the detector measured the intensity of the reflected light with polarization in and perpendicular to the scattering plane. In addition, the samples were presented with right and left handed circularly polarized light. For the two cases where the incident light was circularly polarized, we measured the reflected light in both senses of circular polarization. Eight particulate samples of differing albedo and mixed particle size were used in this study. The reflectance of each sample relative to HALON at 0.633 was measured for each sample. The single scattering albedo, w, was calculated for each sample using the relationship,

$r = \frac{4r}{1+r^2}$ derived by Hapke (1993). The results are reported in Table 1.

Table 1.

Reflectance ans single scattering albedo of the samples

Sample	Reflectance	Single Scattering albedo
MgO	.99	.99997
$BaSO_4$	.99	.99997
S_8	.89	.99666
Fe_2O_3	.38	.7982
MoS_2	.13	.4072
Fe_3O_4	.042	.1547
Co_2O_3	.035	.1307

Eight separate phase curves were measured foı each sample. Two phase curves were measured with the incident light linearly polarized parallel to the scattering plane and the detector measuring the reflected light parallel and perpendicular to the scattering plane, Then two more phase curves were measured with the incident light polarized perpendicular to the scattering plane and the detector measured the intensity of the scattered light linearly polarized parallel and perpendicular to the scattering plane. Then two more phase curves were measured with the sample being presented with right handed circularly polarized light and both senses of circular polarization were measured by the detector. Finally two more phase curves were measured with the sample being presented with left handed circularly polarized light and both senses of circular polarization were measured in the reflected radiation, The eight distinct phase curves were not produced sequentially but instead four measurements were made at each angular setting for linearly polarized light and four more were measured in a separate run for circularly polarized light.

Figure 2 shows the phase curves we determined for the suite of powders. These were produced by summing the measurements of all eight phase curves that were measured as described above. The data are normalized at 10. Figure 3 shows the circular polarization ratio as a function of phase angle as measured for the same suite of samples. This was produced by dividing the intensity of the reflected light that was circularly polarized in the opposite sense to that of the incident beam into the intensity of the reflected light that was in the same circular polarization sense as the incident beam.

The increase in circular polarization ratio with decreasing phase angle is obvious in all of the samples including the absorbing ones. However, it is most pronounced in the HALON, $BaSO_4$, MgO and Sulfur, all of which are highly reflective at the wavelength of the observation. We do not show the linear polarization ratio as a function of phase angle but we report that in all cases the linear polarization ratio decreased with decreasing phase angle.

Discussion

The angularly narrow but intense opposition peak that wc observe in the highly reflective materials cannot bc explained by the shadowing hiding mechanism for the opposition effect. This is because the incident light is expected to be multiply scattered when it encounters highly rcflcctivc materials and hence any shadows or voids would be illuminated and filled in. The reflected radiation would be a mixture of both senses of polarization, The increase in circular polarization ratio with decreasing phase angle, especial] y that sccn in the high] y reflecting materials, is consistent with what would bc expected assuming a cohcrcnt backscattcring mechanism was the cause of the opposition effect.

Comparison of the data displayed in figures 2 and 3 suggests that the materials which exhibit the greatest incrcase in circular polarization near zero phasc have phase curves which increase significantly in this rcgion. in order to test this hypothesis wc measured the slope at 2° of the phase curves in figure 2. Wc plotted the slope against the single scattering albedo for each material and the result.s arc shown in figure 4.

The reflectivity of a material at very small phase angle can bc expressed as the sum of the singly scattered component and the multiply scattered component of the incident radiation. This can be represented by the following expression (after Hapke, 1993):

$$I(g)= B_s f_s(g) w I_{cs} + B_c(w) f_c(w,g) I_{cm}(w),$$

where the first term on the right side is the singly scattered component (due to shadow hiding) and the second term is the multiply scattered component (due to coherent backscattering), and where,

B_s = the amplitude of the phase curve at 0° due to shadow hiding
B_c = the amplitude of the phase curve at 0° due to coherent backscattering
f_s is the shadow hiding phase function
f_c is the coherent backscattering phase function
w = single scattering albedo
wI_{cs} = continuum of the singly scattered radiance at 0°
I_{cm} = continuum of the multiply scattered radiance at 0°

Then

$$\frac{dI}{dg}=B_s\frac{df_s}{dg}wI_{cs}+B_c\frac{df_c}{dg}I_{cm}$$

and

$$\frac{dI/dg}{w}=B_s\frac{df_s}{dg}I_{cs}+B\frac{df_c}{dg}I \quad \text{edge"'}$$

If there were no contribution from coherent backscattering then $\frac{df_c}{dg}=0$

In this case, the slope would change linearly with single scattering albedo. This is not what is observed.

If there were no contribution from shadow hiding then $\frac{df_s}{dg}=0$ and then the slope would change non linearly with single scattering albedo because f_c is a function of w. This is what is seen in the data in figure 4. This supports the hypothesis that shadow hiding is not the cause of the opposition surge seen in highly reflective mater ials. ,

The circular polarization data vs phase information is consistent with the hypothesis that coherent backscattering contributes significantly to the opposition effect observed in highly absorbing materials. In the case of very absorbing materials, the shadow hiding process is expected to make a significant contribution to the observed opposition surge. However, inspection of figure 3 shows that the increase in circular polarization ratio with decreasing phase angle is apparent in for all samples measured including the very absorbing ones. This is consistent with our previous work involving the reflectance if lunar fines (Hapke *et al,* 1993). The shadow hiding model was developed in order to explain the lunar opposition effect yet the information we have learned indicates that even for absorbing regolith materials such as the Moon, coherent backscattering makes a major contribution.

An additional item is interest is that the size of the circular polarization ratio that is shown in figure 3 decreases with the decreasing reflectance of the sample. In order to explore this effect further we have plotted the value of the circular polarization ratio measured at a phase angle of 1° for each sample against the reflectivity of the sample. The result is shown in figure 5. The correlation coefficient is 0.82. This indicates that the contribution of coherent backscattering to the phase curve decreases as the reflectance of the materials decreases.

Figures 4 and 5 indicate a correlation between the shape of the phase curve near 0° and the reflectance of the scattering material. The increase in slope of the phase curve with increase in the reflectance of the sample is not consistent with the shadow hiding model of the opposition effect. Figure 4 shows that there is a corr elation between the size of the circular polarization ratio measured at small phase angle (1°) and the reflectance of the sample. The increase in circular polarization ratio with increasing reflectance of the sample is consistent with the predictions of the coherent backscattering model for the opposition effect.

Conclusion

We have shown that in highly reflective materials coherent backscattering is the principal, and perhaps sole, cause of the opposition effect. The phase curves we have measured for the highly reflective materials are not consistent with the shadow hiding model of the opposition effect. We have also found the unexpected result that coherent backscattering plays a major role in the opposition effect that is seen in highly absorbing materials as well as highly reflecting ones. Prior to this research it was believed that the opposition surge was caused by shadow hiding only. Coherent backscattering is the dominant contributor to the opposition surge at phase angles less than 1°.5. Coherent backscattering is expected to be the cause of the the brightness surges that are observed on high albedo objects such as selected Saturnian and Uranian satellites and Neptune's satellite Triton and it also plays a significant role in the phase curves of less reflective objects such as Mercury, the Earth's moon, and Mars.

This work provides an important foundation for the models which" will be used to analyze spectrophotometric data from NASA's deep space planetary missions particularly Galileo and Cassini. The results of this research can also be applied to existing data sets from missions that have already flown. Ultimately, the technique that we use to measure coherent back-scattering in the laboratory may provide a foundation for future airborne or spacebased remote sensing instruments which could determine the physical properties of a regolith from great distances.

Future Work

The size of the opposition surge and the angular width of the coherent backscattering induced opposition surge peak arc expected to vary as a function of particle size and packing density of the material under observation. Theoretical models treatments of the question make very specific predications for the size of the opposition surge peak as a function of particle size (Mishencko, 1992). However, the physical impossibility of measuring the reflectance at 0° in the laboratory challenges our efforts to rigorous] y test these predications. Nevertheless, near 0° measurements will prove important for constraining theory. We are undertaking measurements near 0° in support of this effort.

A thorough understanding of the coherent backscattering will provide greater insights into the physical properties of planetary regoliths. Specifically it will:

1) Permit inferences to be made regarding the textural characteristics of the surface of a solar system body from observations taken at a spatial resolution that is many of orders of magnitude larger than the scale of the inferred texture. These inferences would be based on observations of the change in slope of the phase curve measured at optical wavelengths, especially at small phase angles.

2) Suggest new ground-based photometric and polarimetric ultraviolet, visual and infrared and/or radar observations of icy satellites which could be used to construct refined interpretations of the textural properties of the satellite regoliths in the context of coherent backscatter theory. This will result in a better understanding of fundamental regolith properties such as grain size, mean grain separation, and albedo.

3) Provide a potentially fruitful line of attack on distinguishing the between two possible causes of the opposition surge seen in the rings of Saturn the first being shadow hiding between the ring particles and the other being the accumulative effect of the individual opposition surges from each particle. It might then provide a useful tool to determine the physical

properties of the particles in other solar system planetary ring systems (Mishchenko and Dlugach, 1992).

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Captions to Figures

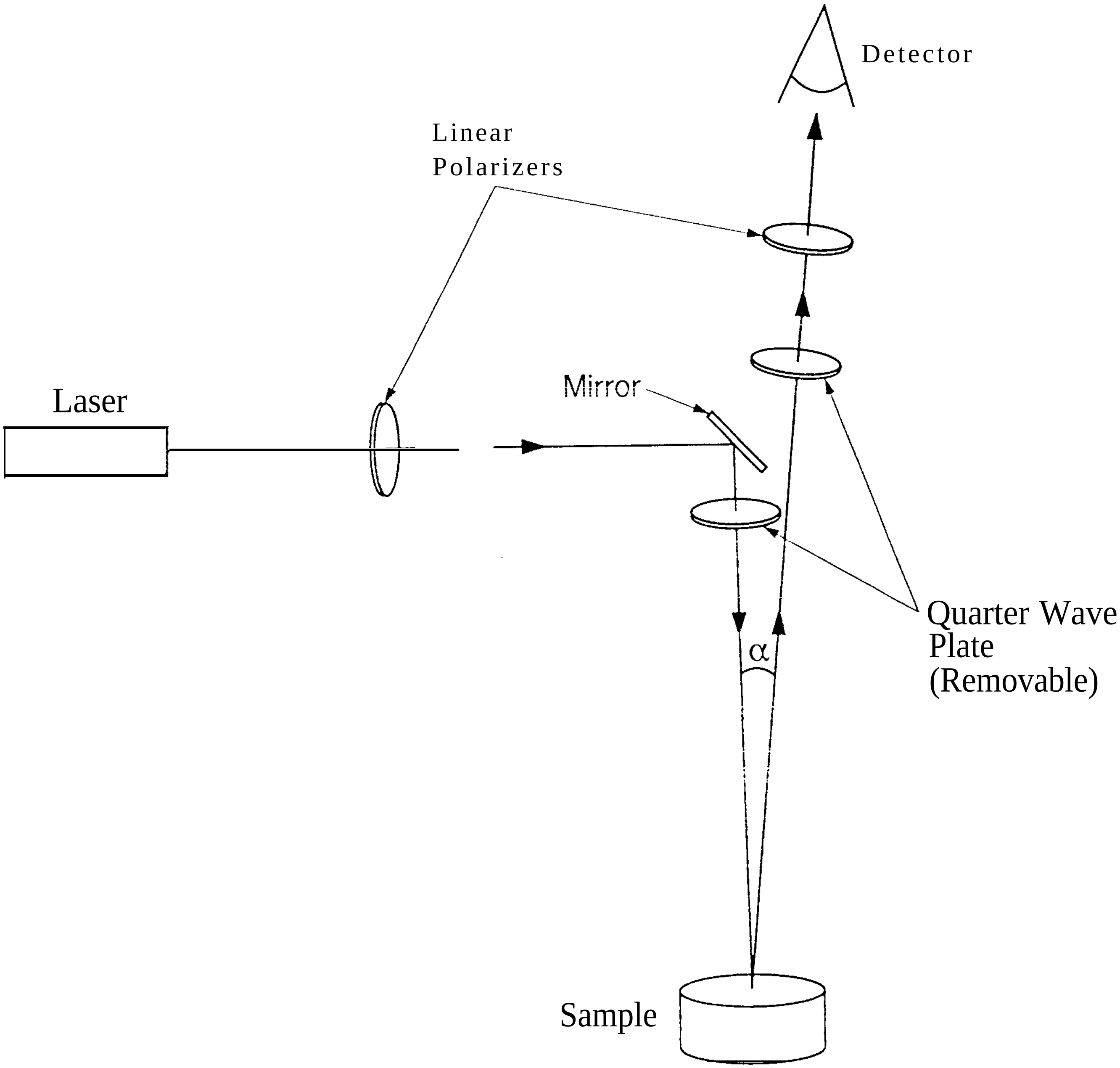
Fig 1. Drawing of the optical path of the laser light that was used in this experiment. This configuration permitted us to present the samples with two orthogonal directions of linearly polarized light, one in the scattering plane and' the other perpendicular to the scattering plane. The addition of the quarter wave plates permitted us to present the samples with both senses of circularly polarized light. This permitted us to determine the phase curves and the circular polarization ratios of each sample as a function of phase angle.

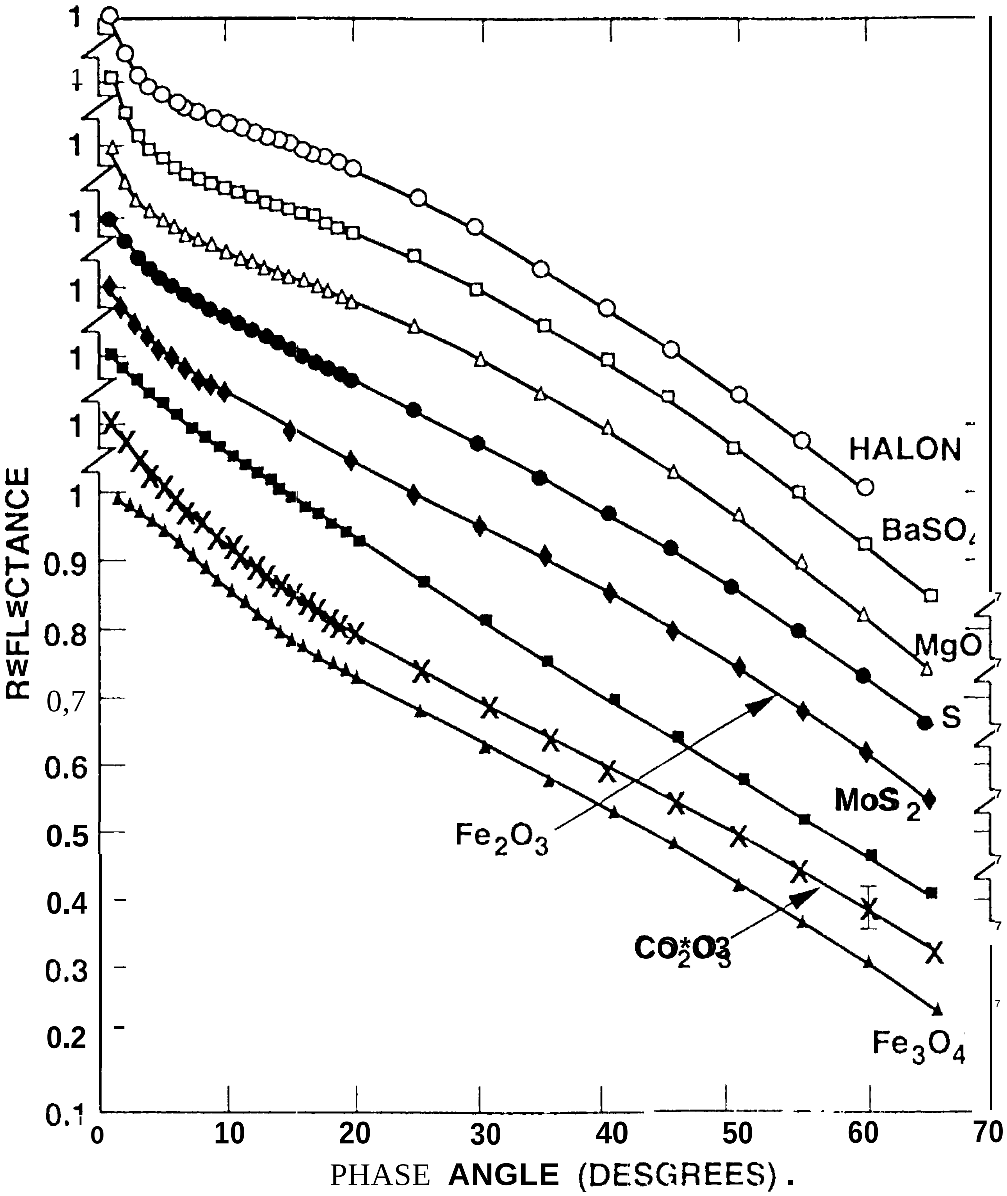
Fig 2. Phase curves of particulate materials with different reflectance. The highly reflective materials (HALON, $BaSO_4$, MgO, and S) all exhibit a strong narrow opposition surge. This effect is not as pronounced in the more absorbing materials. This is not consistent with the expectations of the shadowing hiding model of the opposition effect.

Fig 3. Circular polarization ratios as a function of phase angle of the same materials shown as in Figure 2. The increase in circular polarization ratio with decreasing phase angle is consistent with what is expected if the coherent backscattering mechanism is the cause of the opposition effect.

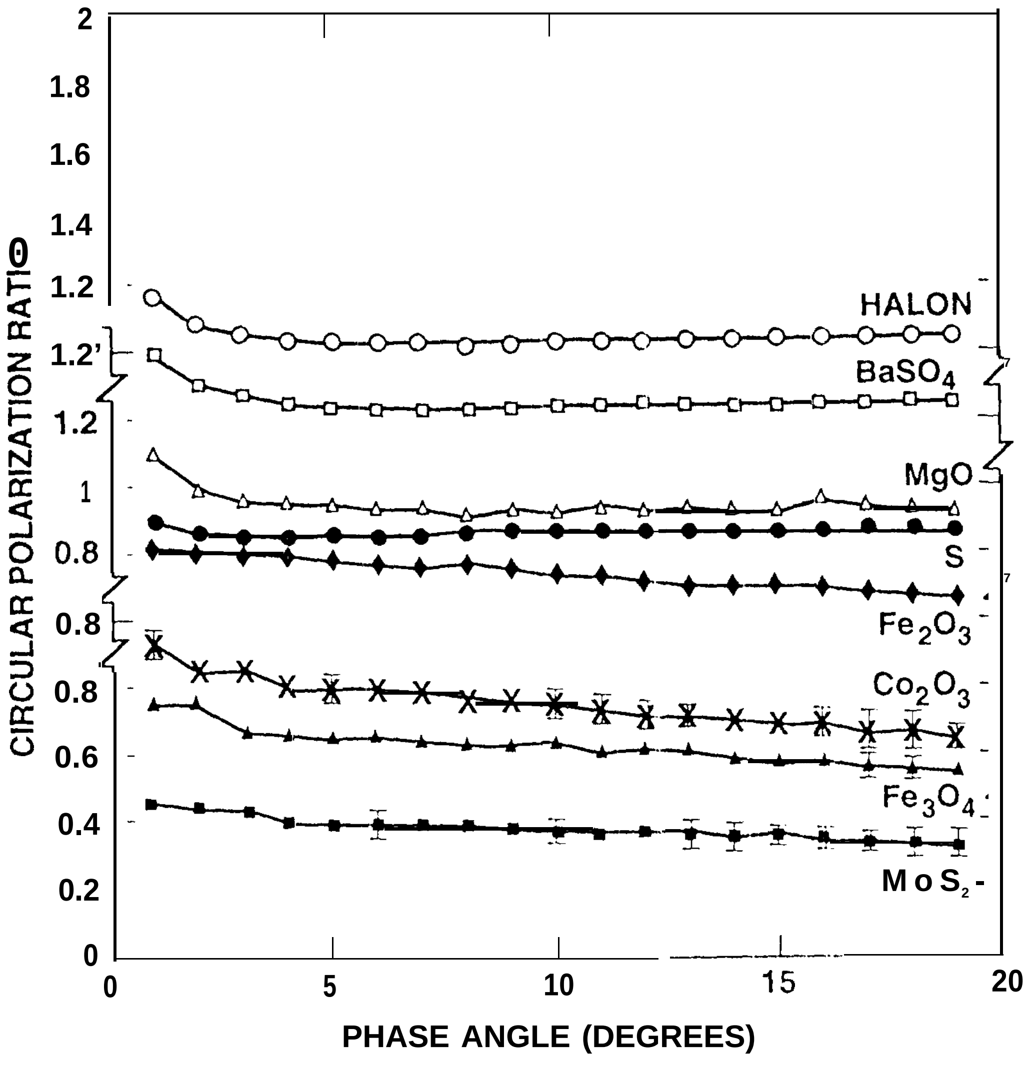
Fig 4. Slope of the phase curves measured at 2° for the samples shown in figure 1 plotted against the single scattering albedo of each material. The increase in the slope of the phase curve with increase in single scattering albedo of the samples is not expected from the shadow hiding model of the opposition effect. This increase is predicted by the coherent backscattering model.

Fig 5. Circular polarization ratio of the samples, measured at 1°, is plotted against the reflectance of the materials. The increase in circular polarization ratio as a function of phase is consistent with the predications of the coherent backscattering model of the opposition effect.

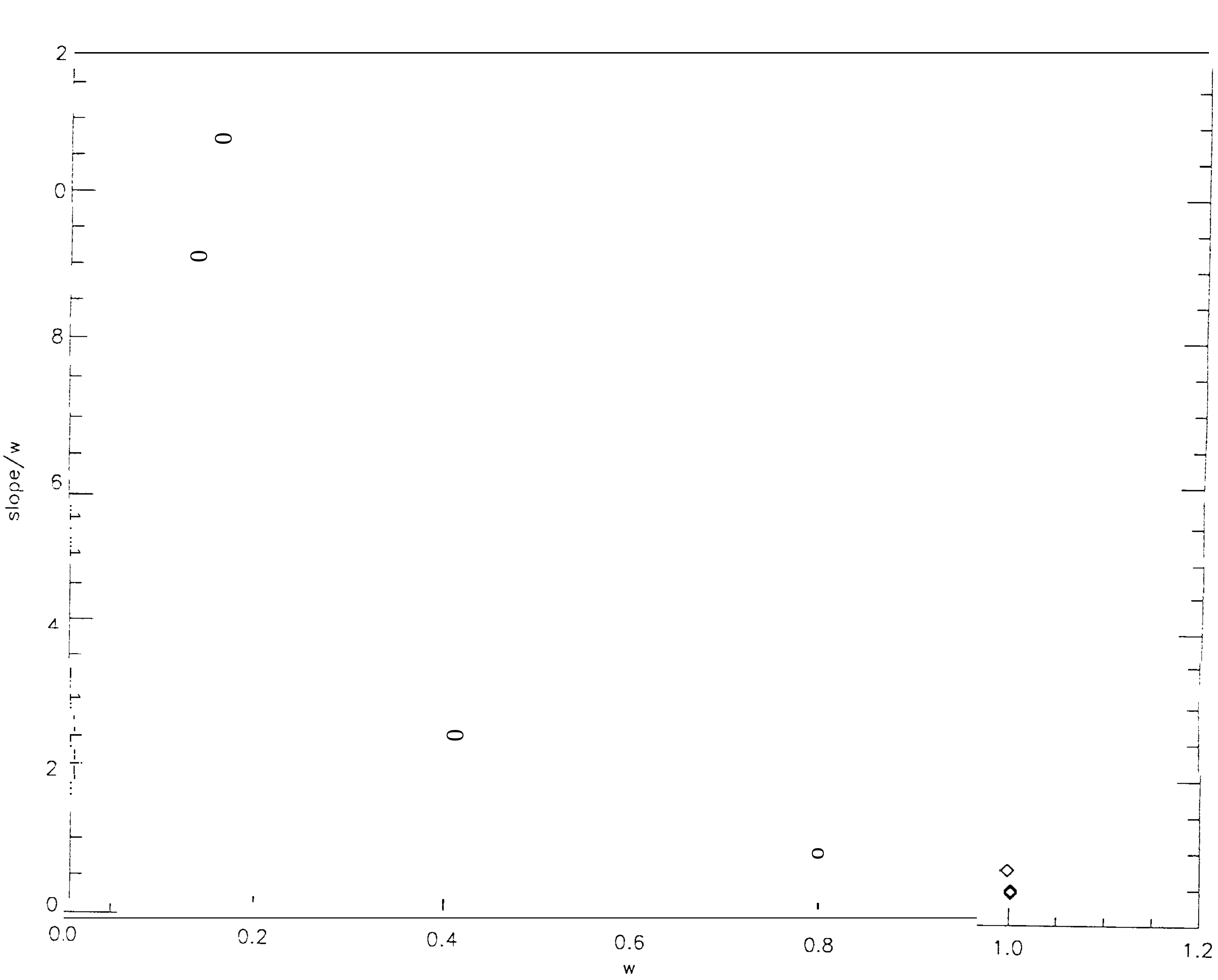

Detector
Linear
Polarizers
Laser
Mirror
α
Quarter Wave
Plate
(Removable)
Sample

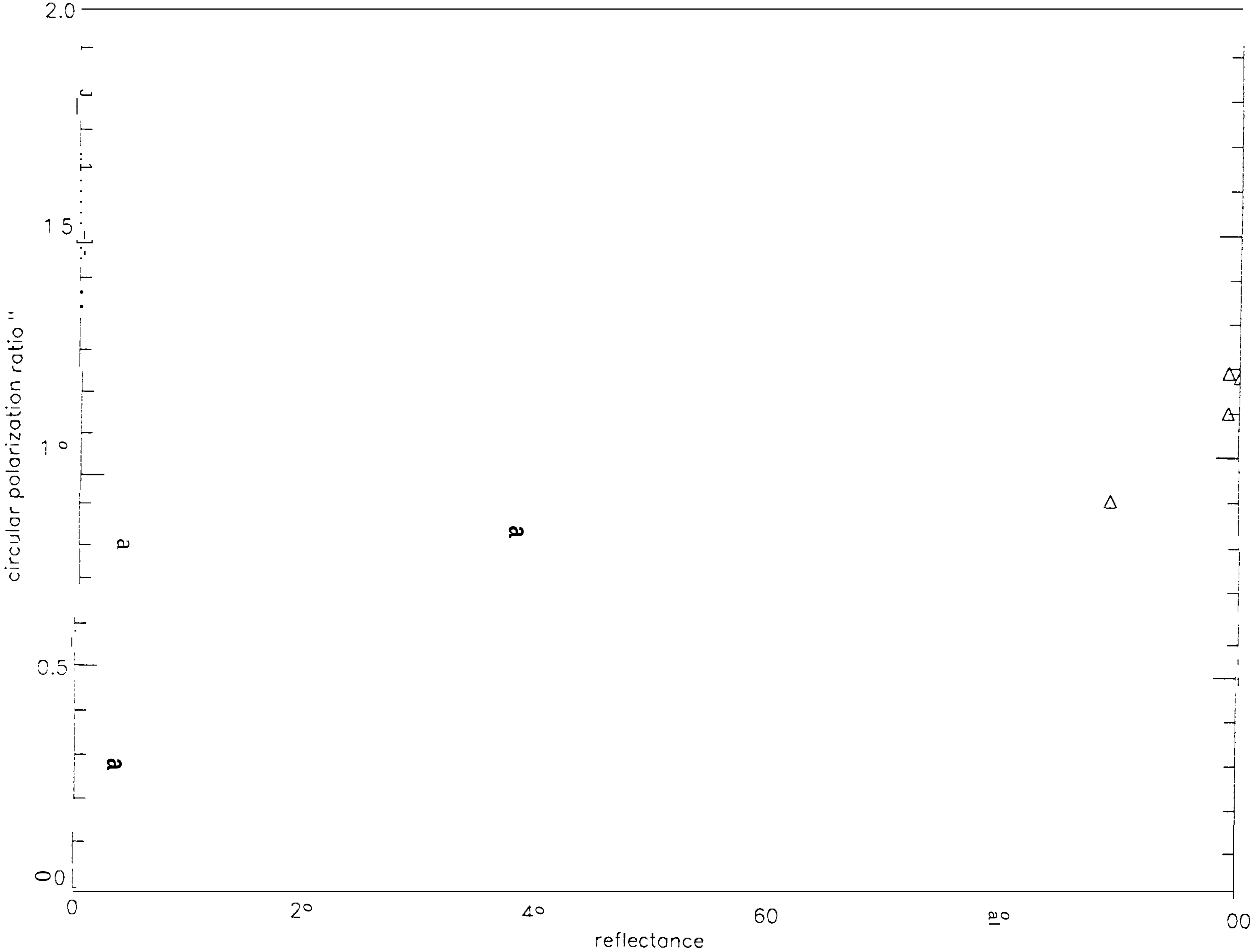


HALON
BaSO₄
MgO
S
MoS 2
Fe2O3
CO2*O3
Fe3O4
REFLECTANCE
1
0.9
0.8
0,7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
70
PHASE ANGLE (DESGREES) .



CIRCULAR POLARIZATION RATIO
2
1.8
1.6
1.4
1.2
1.2'
1.2
1
0.8
0.8
0.8
0.6
0.4
0.2
0
HALON
BaSO4
MgO
S
Fe2O3
Co2O3
Fe3O4
MoS2
0
5
10
15
20
PHASE ANGLE (DEGREES)


slope/w
2
0
8
6
4
2
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
w



circular polarization ratio
2.0
1.5
1.0
0.5
0.0
reflectance
0
20
40
60
80
100

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